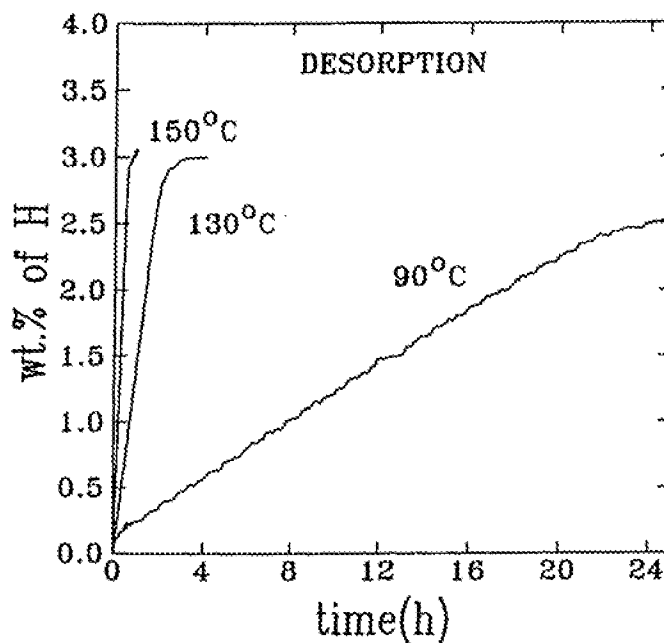




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(21) International Application Number: PCT/CA98/00947 (22) International Filing Date: 7 October 1998 (07.10.98) (71) Applicant (for all designated States except US): MCGILL UNIVERSITY [CA/CA]; 845 Sherbrooke Street West, Montreal, Quebec H3A 1B1 (CA). (72) Inventors; and (75) Inventors/Applicants (for US only): ZALUSKA, Alicja [CA/CA]; 3510 Paul-Emile-Cote, Montreal, Quebec H4E 1Z6 (CA). ZALUSKI, Leszek [CA/CA]; 3510 Paul-Emile-Cote, Montreal, Quebec H4E 1Z6 (CA). STRÖM-OLSEN, John, Olaf [CA/CA]; 443 Lansdowne Avenue, Montreal, Quebec H3Y 2V4 (CA). (74) Agents: MURPHY, Kevin, P. et al.; Swabey Ogilvy Renault, Suite 1600, 1981 McGill College Avenue, Montreal, Quebec H3A 2Y3 (CA).		(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG). Published <i>With international search report.</i>

(54) Title: REVERSIBLE HYDROGEN STORAGE COMPOSITION



(57) Abstract

Hydrogen storage compositions which liberate hydrogen readily and which are readily regenerated from a dehydrogenated state formed by liberation of hydrogen are derived from an AlH_3 -based complex hydride incorporating a member selected from a metalloid such as B, C, Si, P and S, a metal such as Cr, Mn, Fe, Co, Ni, Cu, Mo, Zn, Ga, In and Sn, a metal which forms a stable hydride such as Be, Mg, Ca, Ti, V, Y, Zr and La and a second AlH_3 -based complex hydride.

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REVERSIBLE HYDROGEN STORAGE COMPOSITION

TECHNICAL FIELD

This invention relates to a hydrogen storage composition and to a
5 method of supplying hydrogen.

BACKGROUND ART

Amongst the known metal hydrides, only a few exhibit properties
suitable for reversible hydrogen storage. Reversibility of hydrogen
sorption by a metal hydride means the capability to absorb and desorb
10 hydrogen under practical conditions of hydrogen pressure and temperature.
Most hydrides are either too stable for hydrogenation cycling so that
absorption is easy but desorption of hydrogen requires very high
temperatures; or too unstable so that desorption occurs readily, but
absorption requires extremely high hydrogen pressure.

15 Stable metal hydrides include such compounds as LiH, which melts
at the temperature of 680°C but decomposes at an even higher temperature
of 720°C, TiH₂, CaH₂ and ZrH₂, which have to be heated up to 650°C,
600°C and 880°C, respectively, in order to release hydrogen. Re-
hydrogenation of these hydrides is, however, easy and they absorb
20 hydrogen readily even under low hydrogen pressure.

From the group of unstable metal hydrides, AlH₃ and LiAlH₄ are the
most characteristic examples, having such a high equilibrium pressure of
hydrogen that gaseous hydrogenation is in practice impossible. Only
chemical reactions are effective for the formation of these unstable
25 hydrides. On the other hand, both AlH₃ and LiAlH₄ desorb hydrogen
readily at temperatures between 100°C and 130°C and with good kinetics.

So far, the only materials which exhibit practical, reversible
properties, i.e., hydrogenation/dehydrogenation at ambient conditions, for

example, LaNi_5 , FeTi or Ti-V , have a hydrogen capacity of less than 2 wt.%, which is too low for practical applications.

DISCLOSURE OF THE INVENTION

The invention provides hydrogen storage compositions capable of
5 reversible operation at moderately elevated temperatures of 80-180°C, typically 100-150°C, and having a hydrogen capacity exceeding 2 wt.%.

In accordance with one aspect of the invention there is provided a hydrogen storage composition comprising i) an AlH_3 -based complex hydride incorporating ii) at least one member selected from the group
10 consisting of a) an element that does not readily form a hydride in a solid-state form, b) a metal which forms a stable metal hydride, c) a hydride of a metal of b), d) an AlH_3 -based complex hydride different from said complex i).

In accordance with another aspect of the invention there is provided
15 a composition of the invention in a dehydrogenated state.

In accordance with yet another aspect of the invention there is provided a method of supplying hydrogen comprising liberating hydrogen from a composition of the invention at a temperature of at least 80°C with formation of a dehydrogenated form of the composition, removing the
20 liberated hydrogen, and absorbing hydrogen in the dehydrogenated form to regenerate the AlH_3 -based complex hydride as a future source of hydrogen.

In this specification reference to a "dehydrogenated form" or "dehydrogenated state" refers to a form or state of the hydrogen storage composition of the invention resulting from liberation of hydrogen from the
25 composition. It is not intended to indicate that complete dehydrogenation has necessarily occurred, and contemplates both a complete dehydrogenation and a partial dehydrogenation resulting from liberation of at least part of the hydrogen content of the composition.

The reference to an AlH_3 -based complex hydride refers to those complex metal hydrides such as NaAlH_4 or LiAlH_4 which liberate hydrogen readily at moderate temperatures of the order of 100 to 150°C, forming a dehydrogenated form or state from which the hydride form can not be regenerated with hydrogen gas, or which can only be regenerated under extreme conditions impractical in a reversible hydrogen storage composition. These AlH_3 -based complex hydrides are sometimes referred to as being "unstable" in view of their ease in liberating hydrogen and the difficulty in regeneration from the dehydrogenated form.

10 DETAILED DISCLOSURE OF THE INVENTION

The invention is based on the discovery, that properties of these so-called unstable metal hydrides, which decompose easily but are very difficult to re-hydrogenate, can be altered in such a way that the required re-hydrogenation conditions are much more favourable and the hydride can be regenerated with hydrogen gas in a practical operation.

The alteration of the unstable metal hydride may be achieved by changing the chemical composition of the hydride, accompanied by mechanical grinding.

More especially the invention is concerned with hydrides based on AlH_3 -complex. AlH_3 is very unstable and decomposes spontaneously at temperatures above 100°C. Normally, AlH_3 can not be rehydrogenated, even at extremely high hydrogen pressures, after hydrogen has been liberated from it. The same applies to other hydrides based on AlH_3 complex, for example, LiAlH_4 , NaAlH_4 , $\text{Mg}(\text{AlH}_4)_2$ and $\text{Ca}(\text{AlH}_4)_2$. These hydrides offer very high hydrogen capacities, typically up to 7-wt.%, and desorb hydrogen easily at temperatures between 100°C and 180°C, but normally can not be rehydrogenated at hydrogen pressures lower than 100 atmospheres.

In this invention, properties of such unstable hydrides are changed by incorporating in them other elements or hydrides, typically the incorporation may be by alloying the components together by, for example, mechanical grinding or ball milling.

5 A large variety of unstable AlH_3 -based hydrides have been investigated with different alloying components, and such alloying is found to produce dramatic change in the hydrogenation properties of the AlH_3 -based hydrides. As a consequence, the hydrides become reversible for practical applications because rehydrogenation can be performed at much
10 lower hydrogen pressures.

Typical AlH_3 -based complex hydrides employed in the invention may be represented by formula (I):



wherein M is a metal; x is an integer of 1 to 3, y is an integer of 1 or 2, and
15 z is equal to x or 2x. Preferred examples of M are Li, Na, Be, Mg and Ca, and preferably x is 1 or 3.

Suitable AlH_3 -based complex hydrides for use in the invention include LiAlH_4 , NaAlH_4 , $\text{Mg}(\text{AlH}_4)_2$, $\text{Be}(\text{AlH}_4)_2$, $\text{Zr}(\text{AlH}_4)_2$, $\text{Ca}(\text{AlH}_4)_2$, Li_3AlH_6 and Na_3AlH_6 all of which change their hydrogen sorption
20 properties when mechanically ground or ball milled in the presence of at least one member selected from the following Groups:

1. elements that do not form hydrides in a solid-state form under normal conditions, for example, metalloids such as B, C, Si, P and S, and metals such as Cr, Mn, Fe, Co, Ni, Cu, Mo, Zn, Ga, In and Sn;
- 25 2. elements which form relatively stable metal hydrides, such as Be, Mg, Ca, Ti, V, Y, Zr and La;
3. hydrides of the elements from Group 2 above such as BeH_2 , MgH_2 , CaH_2 , TiH_2 , VH_2 , YH_2 , ZrH_2 and LaH_2 ;

4. other hydrides based on the AlH_3 -complex.

These additions, alone or in mixtures, are able to change the sorption properties of the AlH_3 -based complex hydrides. The mechanism of the change is not fully understood, but it is probable that different mechanisms

5 are involved with the different classes of additive.

The probable mechanisms of altering hydrogenation properties of AlH_3 -based hydrides are as follows:

i) interstitial alloying of the AlH_3 -based hydride.

This mechanism is most probable in the case of metalloids as, for
10 example, boron and carbon.

ii) substitutional alloying accompanied by catalysis.

This mechanism is expected to apply to most metal additions from group 2 elements.

iii) synergetic effect of hydrogen sorption in mixtures of hydrides.

15 This mechanism was found in mixtures of AlH_3 -based hydrides with hydrides of groups 3 and 4 above and also as a result of ball milling with elements from group 2 above. In the latter case, however, formation of the respective hydrides, listed in group 3, can occur during hydrogenation/dehydrogenation cycling of the main AlH_3 -based hydride.

20 Depending on the addition, there are essentially two kinds of behaviour of hydride mixtures. One is of a kinetic character, when the basic hydride does not react with the addition. In this case the addition acts as a hydrogen carrier or catalyst and improves the reaction kinetics. The second mechanism is based on formation of new complex hydrides or more
25 complicated hydride complexes. In this case thermodynamic properties of the main AlH_3 -based hydride are significantly altered, resulting in changed equilibrium pressures for hydride formation.

The above mechanisms for the improvement of hydrogen sorption properties of AlH_3 -based complex hydrides, as a result of changes in the chemical compositions by means of mechanical alloying with additions, were studied in various AlH_3 -based complex hydrides with a number of additions from the above groups of materials. Within one family of additions, the amounts of additions were varied.

Typically the molar ratio of the AlH_3 -based complex hydride to the addition was changed in the range between 10 : 1 to 1 : 3. Samples of AlH_3 -based complex hydrides with no additions at all, but ball milled at the same conditions as the samples with additions, were also studied. As a general conclusion it was found that in each case ball milling alone improved kinetic properties of the AlH_3 -based complex hydride, but ball milling with additions improved them much more remarkably and evidently could change thermodynamical properties of the main hydride.

Although the detailed nature of these changes has not been fully determined, some general conclusions can be described as follows, in connection with the mechanisms proposed above.

Interstitial character of alloying with metalloids is confirmed by x-ray diffraction analysis. For example, addition of C to NaAlH_4 in the molar proportion of 1 : 1 does not change the x-ray diffraction pattern of NaAlH_4 and no other reflections were observed which could indicate formation of other phases. Also, no reflections or halos from crystalline or amorphous carbon can be seen in the x-ray diffraction pattern. At the same time, however, this material exhibits hydrogenation properties which differ dramatically from conventional NaAlH_4 . As reported previously [1, 2] NaAlH_4 has such a high equilibrium pressure of hydrogenation that it was normally impossible to re-hydrogenate it after decomposition. Only recently Bogdanovic discovered a catalyst that enabled rehydrogenation of

NaAlH₄ [3, 4]. However, a very high hydrogen pressure of 150 atm was still necessary to perform absorption at 170°C.

A material according to the present invention, being a ball milled mixture of NaAlH₄ and C exhibits reversible hydrogen sorption properties at much lower pressures and with much faster kinetics. Equilibrium pressure for this material is, for example, about two times lower at 140°C, than the reported values for conventional NaAlH₄ [1, 2]. This means that much lower hydrogen pressures are required to effectively perform hydrogen absorption. Moreover, kinetics of the hydrogenation/-dehydrogenation cycles remarkably exceeds the reaction rates observed not only for the conventional NaAlH₄, but also for the catalysed NaAlH₄ of the prior art [3, 4]. For example, the catalysed NaAlH₄ desorbs 2 wt.% of hydrogen at 160°C within about 6 hrs. [3, 4], while NaAlH₄ with C of the invention can desorb the same amount of hydrogen within only 30 min. For comparison, conventional NaAlH₄ without catalyst requires more than 50 hrs. at 160°C to desorb 2 wt.% of hydrogen.

In another example boron is found to be very effective in changing the hydrogen sorption properties of different AlH₃-based complex hydrides. In complex hydrides boron shifts the equilibrium pressure of hydrogen towards lower pressures, i.e., stabilizes the AlH₃-based complex hydride. This is very advantageous because as a result these hydrides can effectively operate at lower hydrogen pressures.

Addition of silicon also results in significantly enhanced kinetics of hydrogenation cycling of the AlH₃-based complex hydrides.

Additions of metals, for example, Cu, Ni, Fe and Zn also improve sorption properties of AlH₃-hydride complexes. The presence of Cu, Fe or Mn can be seen in the x-ray diffraction pattern, but with a clearly reduced

size of the metal grains, which is very advantageous from the point of view of the possible catalytic action of the additions.

AlH_3 -based complex hydrides ball milled with elements which easily form hydrides, from group 2 above, are among the most interesting materials because of the variety of the possible combinations of the hydride mixtures. The additions can be introduced into the mixture in the form of elements or their hydrides, according to groups 2 and 3 above. Ball milling with these additions results in the formation of hydride complexes with changed thermodynamical properties. For example, ball milling of NaAlH_4 with zirconium or with its hydride results in such a change of the equilibrium pressure that effective absorption of hydrogen can be performed at 60 to 80 atm instead of 150 atm., as reported previously for catalysed NaAlH_4 [3, 4]. Kinetics of hydrogenation cycling are also many times faster at similar temperatures than catalysed NaAlH_4 . Excellent hydrogen sorption properties appear to be even more enhanced when the mixtures are in the nanocrystalline form, with the components being extremely finely intermixed.

Suitably the AlH_3 -based complex hydride and the additive from one or more of groups 1, 2, 3 and 4 above, have a particle size below 100 μm , preferably below 50 μm .

The hydrogen storage compositions of the invention liberate hydrogen at a temperature of at least 80°C, generally 80 to 180°C and typically 100 to 180°C.

Hydrogen absorption into the dehydrogenated form of the hydrogen storage composition of the invention is suitably carried out at a temperature of 80 to 150°C typically 100 to 150°C, and a hydrogen pressure of 20 to 100, preferably 30 to 80 atm for a period of 0.25 to 5 hours, preferably 0.5 to 3 hours.

The hydrogen storage compositions of the invention have a hydrogen capacity of 2 to 7, more usually 3 to 7 wt.%.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 illustrates graphically desorption of hydrogen from a hydrogen storage composition of the invention, based on NaAlH_4 and C;

FIG. 2 illustrates graphically hydrogen absorption during regeneration from the dehydrogenated form of the composition of Fig. 1;

FIG. 3 illustrates graphically hydrogen desorption from a hydrogen storage composition of the invention, based on NaAlH_4 and Cu;

FIG. 4 illustrates graphically hydrogen absorption from a hydrogen storage composition of the invention, based on NaAlH_4 and Zn;

FIG. 5 illustrates the diffraction pattern of a hydrogen storage composition of the invention derived from NaAlH_4 and Zr after long (18h) and short (1h) milling time;

FIG. 6 illustrates graphically desorption of hydrogen from the storage composition of Fig. 5; and

FIG. 7 illustrates graphically hydrogen desorption from a hydrogen storage composition of the invention, based on NaAlH_4 and LiAlH_4 .

EXAMPLES

Example 1

NaAlH_4 was ball milled with an addition of C in a high-energy ball mill SPEX 8000 (Trade-mark). The molar ratio of the hydride to C was 3:1. After ball milling the mixture was placed in an automated gas titration system and subjected to hydrogenation/dehydrogenation cycles. The material was able to desorb about 3 wt.% at temperatures as low as 90°–150°C (Fig. 1), with an additional 1.5 wt.% being released at about 160°C.

Rehydrogenation was performed at about 80 atm at a temperature of 130°C and was completed within 2 to 3 hours (Fig. 2).

Example 2

NaAlH₄ was ball milled in a high-energy ball mill, with additions of
5 metals that normally do not form metal hydrides, i.e. Cu and Zn. In both cases the molar ratio of the hydride to metal was 4 : 1. The subsequent hydrogenation/dehydrogenation cycles showed efficient desorption and absorption at temperatures and under hydrogen pressure at which conventional NaAlH₄ could never operate (Figs. 3 and 4).

10 Example 3

NaAlH₄ was ball milled with addition of zirconium, added at a molar ratio of 4 : 1. After ball milling the material exhibited extremely fine microstructure which was seen in the x-ray diffraction pattern, all Bragg's reflections being nearly vanished (Fig. 5). For comparison, x-ray
15 diffraction pattern of another mixture of NaAlH₄ + Zr (3 : 1, shorter milling time) is also presented in Fig. 5. As compared to the conventional NaAlH₄, this material exhibits outstanding hydrogenation properties with fast hydrogen desorption at temperatures between 110 and 150°C (Fig. 6) and rehydrogenation at hydrogen pressures of 50-80 atm. Similar
20 hydrogenation performance is obtained when zirconium is introduced in the form of zirconium hydride, ZrH₂, instead of Zr.

Example 4

LiAlH₄ ball milled with Mg was investigated by differential scanning calorimetry (DSC, Perkin-Elmer). Comparison of the DSC traces
25 for the hydrogen evolution showed that the sample containing magnesium desorbed hydrogen at higher temperatures than the sample without additions. This means that stability of the hydride with magnesium was increased, leading to lower hydrogen pressures required for

rehydrogenation. The same was confirmed by desorption measurements in the gas titration system. Similar increase of the stability of LiAlH_4 can be also obtained after ball milling with magnesium hydride instead of magnesium.

5 Example 5

A mixture of two hydrides: NaAlH_4 and LiAlH_4 in a molar ratio of 1:1, was ball milled in a high energy ball mill (SPEX 8000). As a result, the mixture exhibited great improvement in the desorption kinetics (Fig. 7), as compared to the conventional desorption of NaAlH_4 and LiAlH_4 .

10 References

- [1] T. N. Dymova, N. G. Eliseeva, S. Bakum and Y. M. Dergachev *Dolk, Akad. Nauk SSSR*, Vol. 215, p. 1369, 1974.
- [2] T. N. Dymova, Y. M. Dergachev, V. A. Sokolov and N. A. Grechanaya *Dolk, Akad. Nauk SSSR*, Vol. 224, No. 3, p. 591, 1975.
- 15 [3] B. Bogdanovic and M. Schwickardi, *J. Alloys and Comp.*, Vol. 253, p. 1, 1997.
- [4] B. Bogdanovic, *German Pat. Appln. No. 195 26 434.7*, 1995.

CLAIMS

1. A hydrogen storage composition comprising
 - i) an AlH_3 -based complex hydride incorporating
 - ii) at least one member selected from the group consisting of:
 - 5 a) an element that does not readily form a hydride in a solid-state form,
 - b) a metal which forms a stable metal hydride,
 - c) a hydride of a metal of b), and
 - d) an AlH_3 hydride complex different from said
- 10 complex i).
2. A composition according to claim 1, wherein said member is a said element a) being a metalloid selected from B, C, Si, P and S.
- 15 3. A composition according to claim 1, wherein said member is a said element a) being a metal selected from Cr, Mn, Fe, Co, Ni, Cu, Mo, Zn, Ga, In and Sn.
4. A composition according to claim 1, wherein said member is a said
- 20 metal b) selected from Be, Mg, Ca, Ti, V, Y, Zr and La.
5. A composition according to claim 1, wherein said member is a said hydride c) selected from BeH_2 , MgH_2 , CaH_2 , TiH_2 , VH_2 , YH_2 , ZrH_2 and LaH_2 .
- 25 6. A composition according to claim 1, wherein said member is a said hydride complex d).

7. A composition according to any one of claims 1 to 6, wherein the AlH_3 -based complex hydride i) is of formula (I):



wherein

- 5 M is a metal,
 x is an integer of 1 to 3,
 y is an integer of 1 or 2, and
 z is equal to x or 2x.

10 8. A composition according to claim 7, wherein M is selected from Li, Na, Be, Mg and Ca and x is 1 or 3.

9. A composition according to any one of claims 1 to 8, wherein said AlH_3 -based complex hydride is selected from LiAlH_4 , NaAlH_4 , $\text{Mg}(\text{AlH}_4)_2$,
15 $\text{Be}(\text{AlH}_4)_2$, $\text{Zr}(\text{AlH}_4)_2$, $\text{Ca}(\text{AlH}_4)_2$, Li_3AlH_6 and Na_3AlH_6 .

10. A composition according to any one of claims 1 to 9, having a molar ratio of said hydride to said member of 10 : 1 to 1 : 3.

20 11. A composition according to any one of claims 1 to 10, wherein said member is alloyed with said hydride by ball milling.

12. A composition according to any one of claims 1 to 11, which liberates hydrogen at a temperature above 80°C to produce a material
25 which is a dehydrogenated state of said composition, said material being adapted to absorb hydrogen to regenerate said hydrogen storage composition.

13. A composition of claim 12, in said dehydrogenated state.

14. A method of supplying hydrogen comprising liberating hydrogen from a composition as defined in any one of claims 1 to 12, at a
5 temperature of at least 80°C with formation of a dehydrogenated form of said composition,

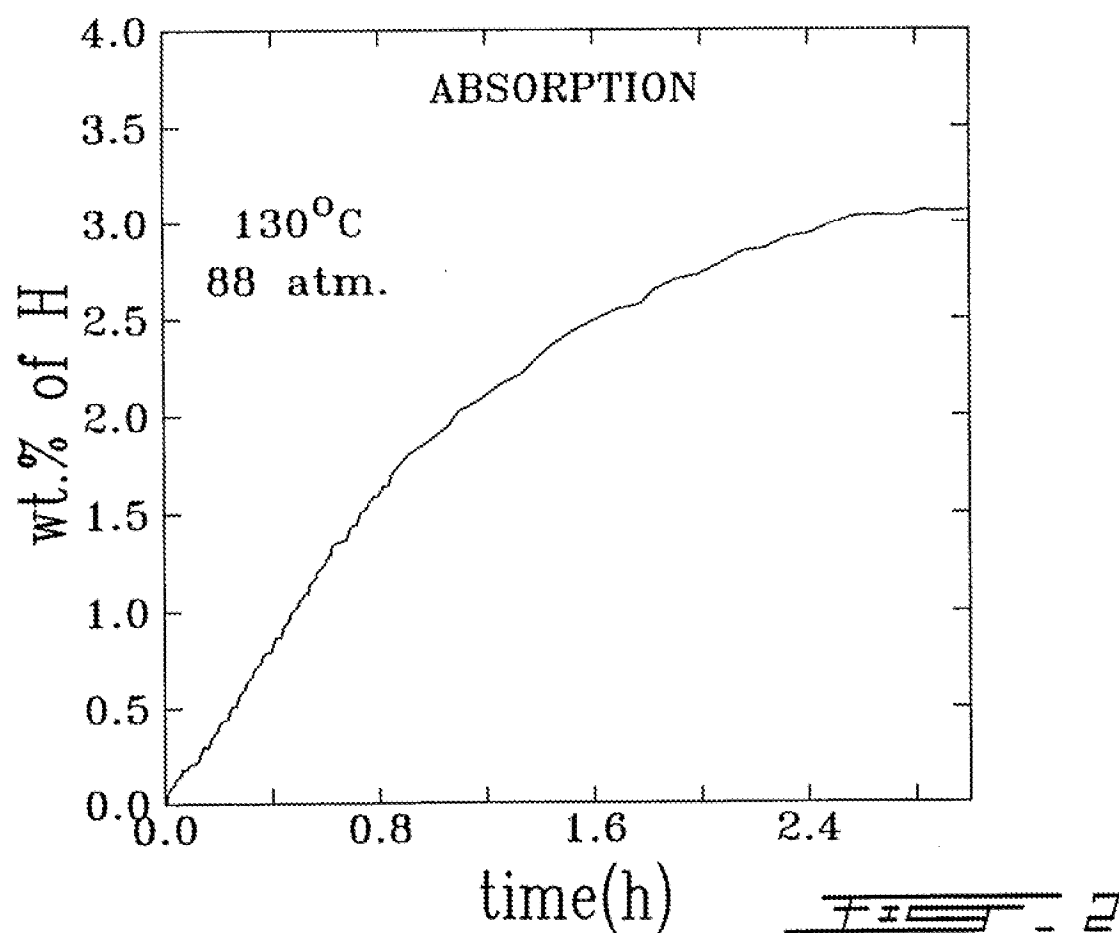
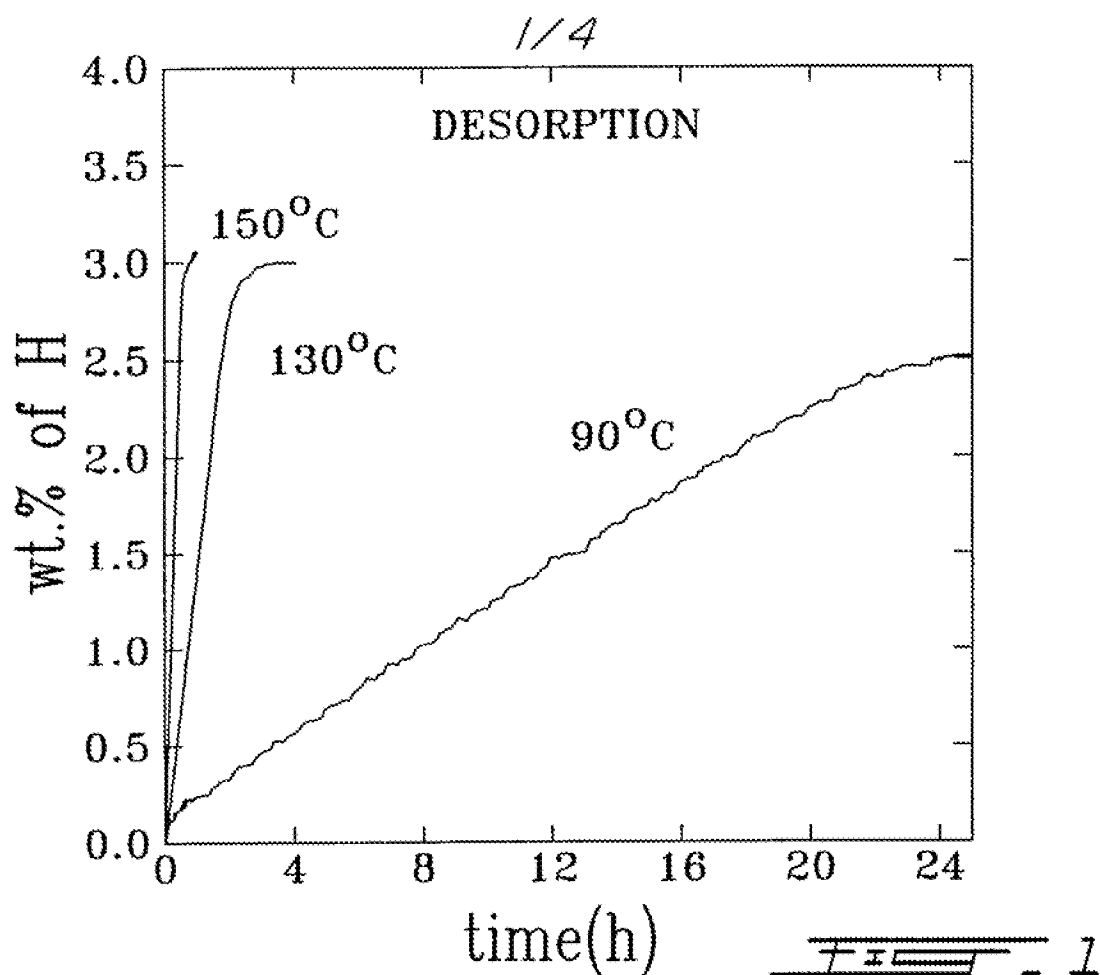
removing said liberated hydrogen, and

absorbing hydrogen in said dehydrogenated form to regenerate said composition as a future source of hydrogen.

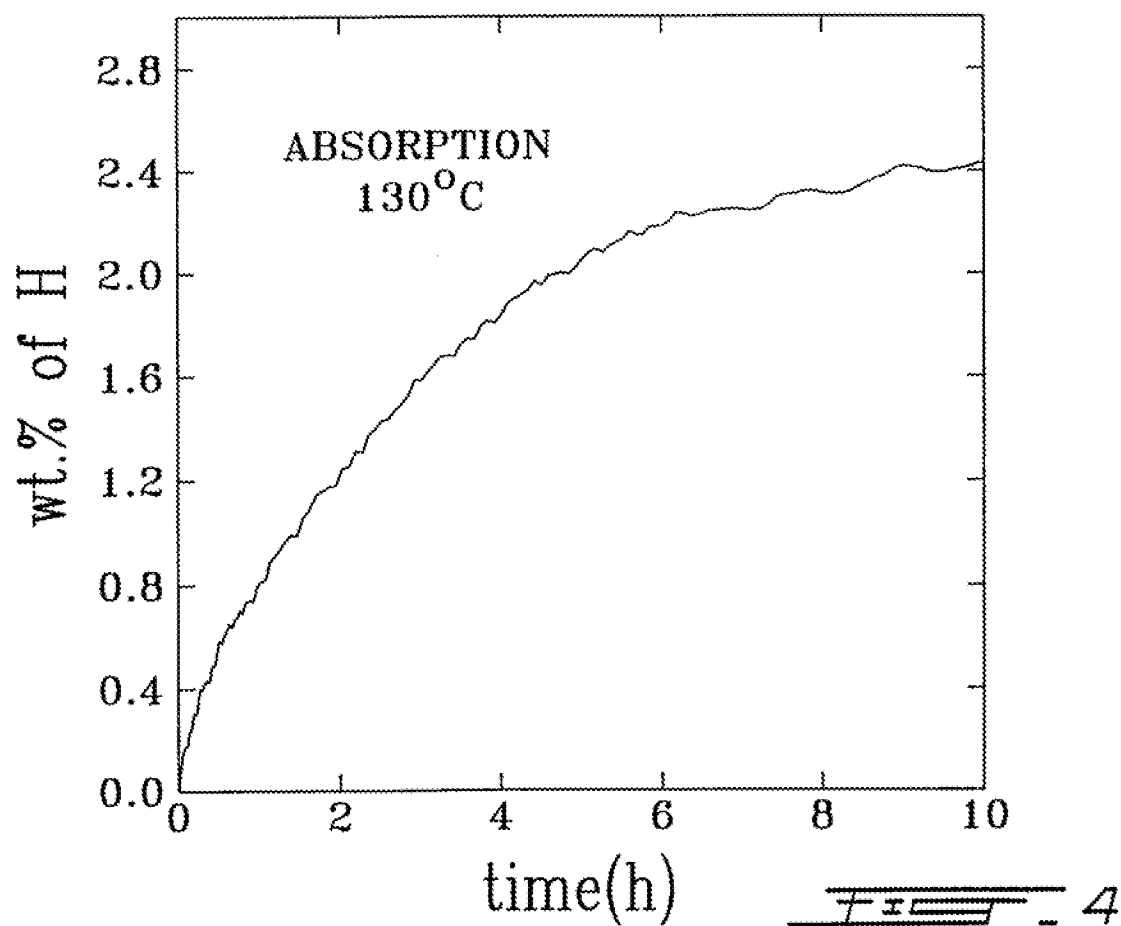
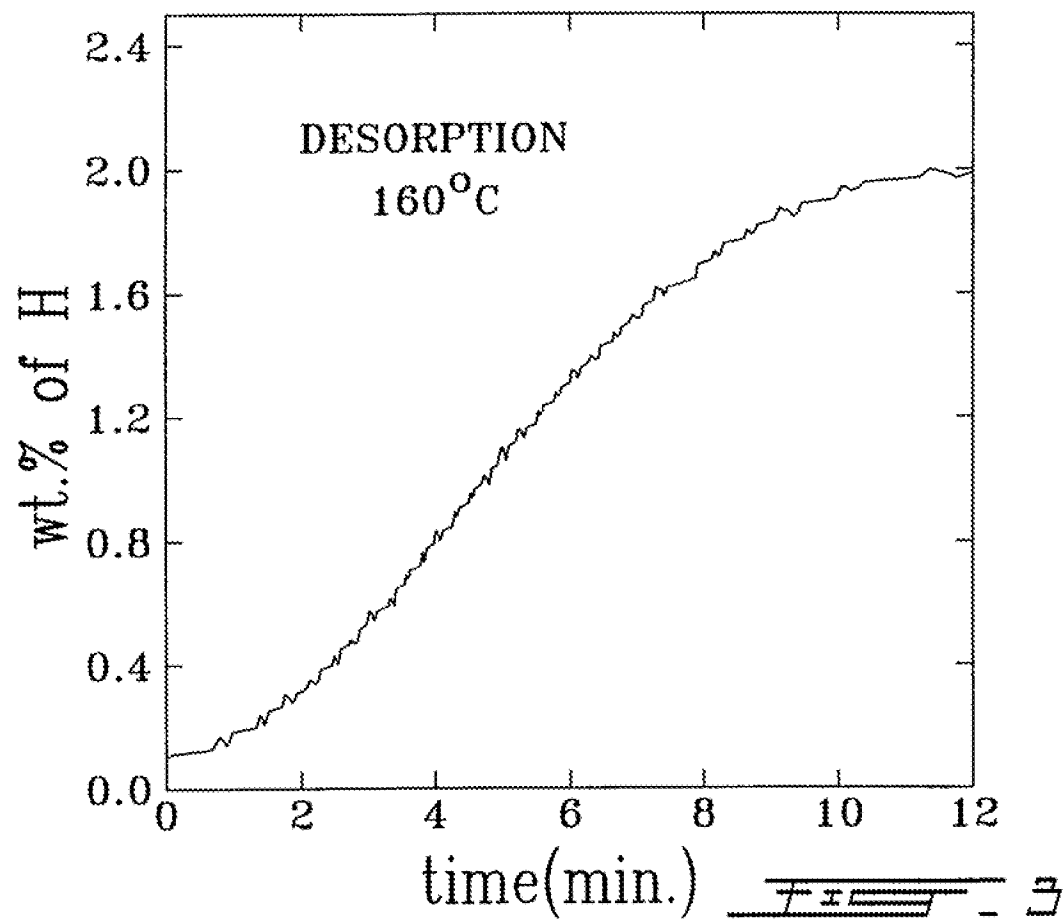
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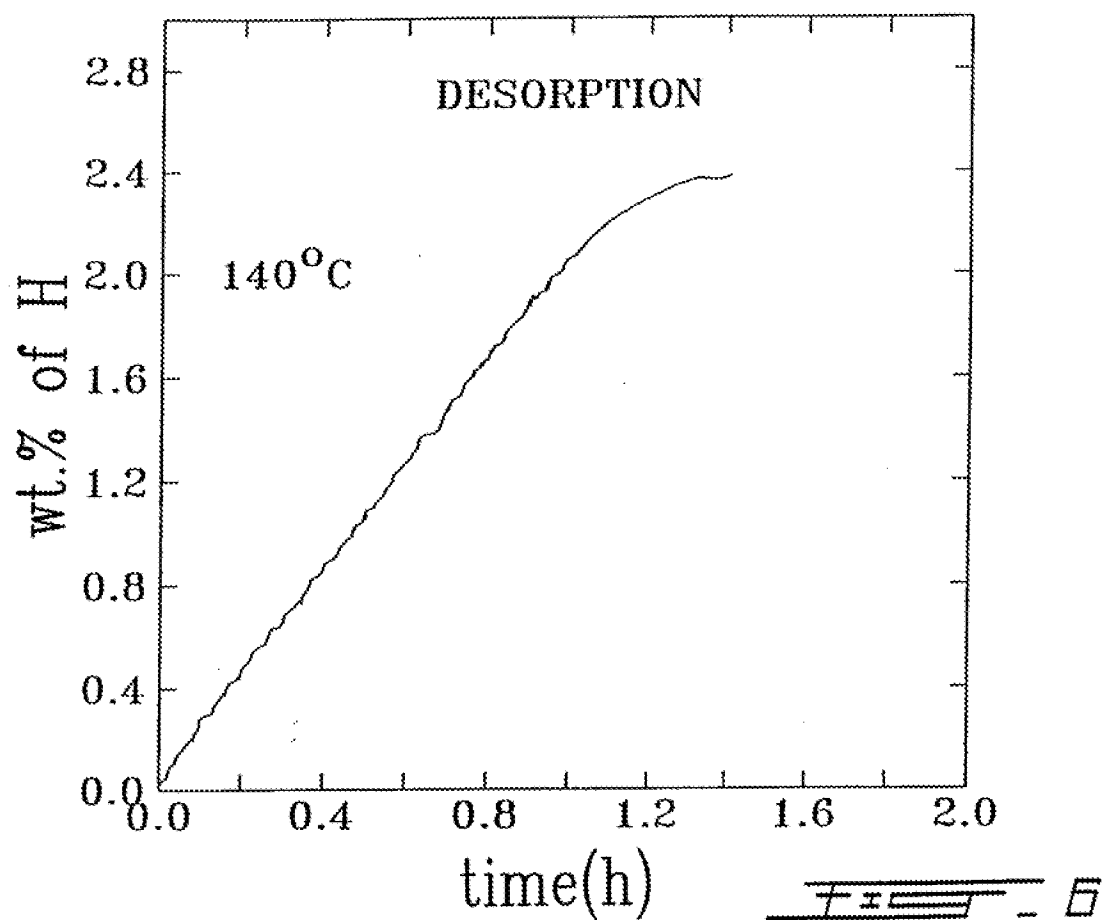
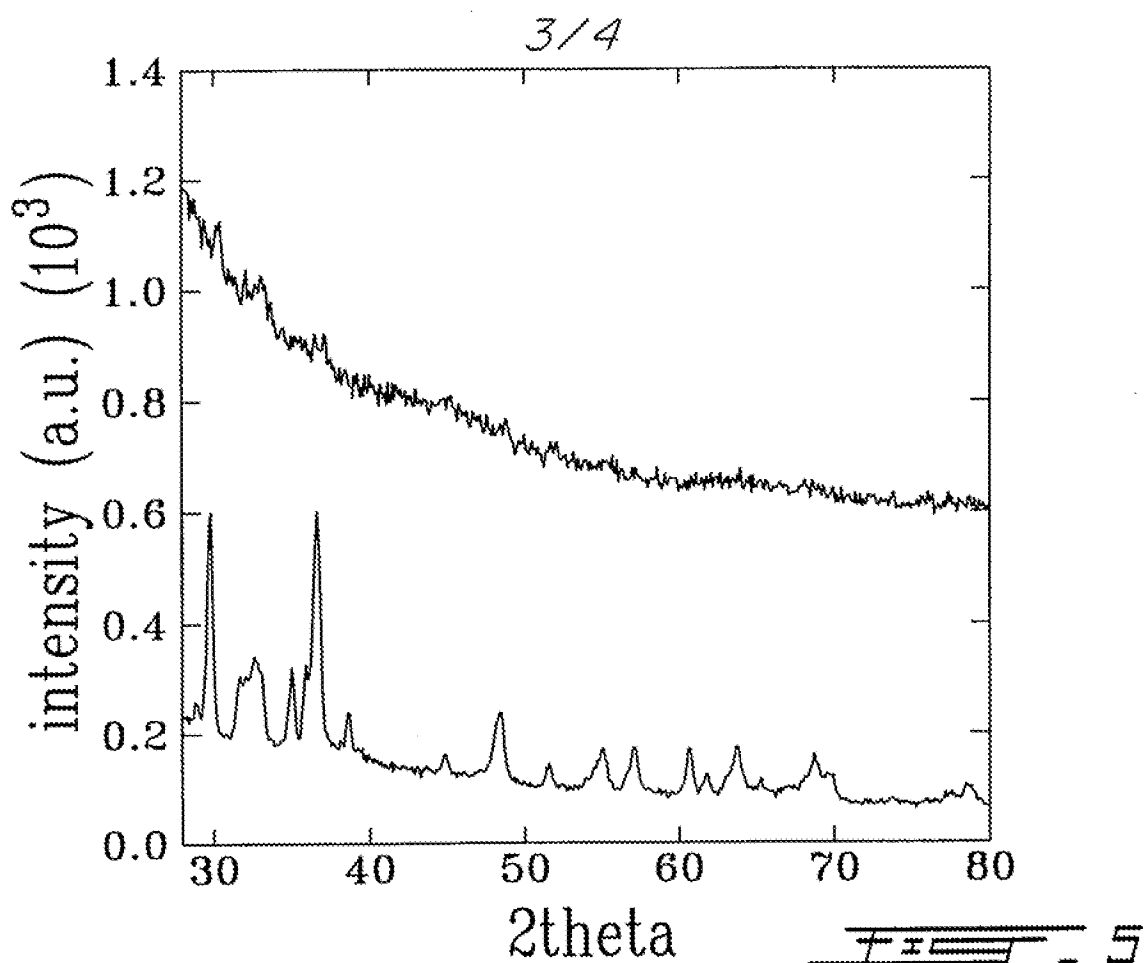
15. A method according to claim 14, wherein said temperature is 80 to 180°C.

16. A method according to claim 14 or 15, wherein said absorbing of
15 hydrogen is carried out at a temperature of 80 to 150°C and a hydrogen pressure of 20 to 100 atmospheres.

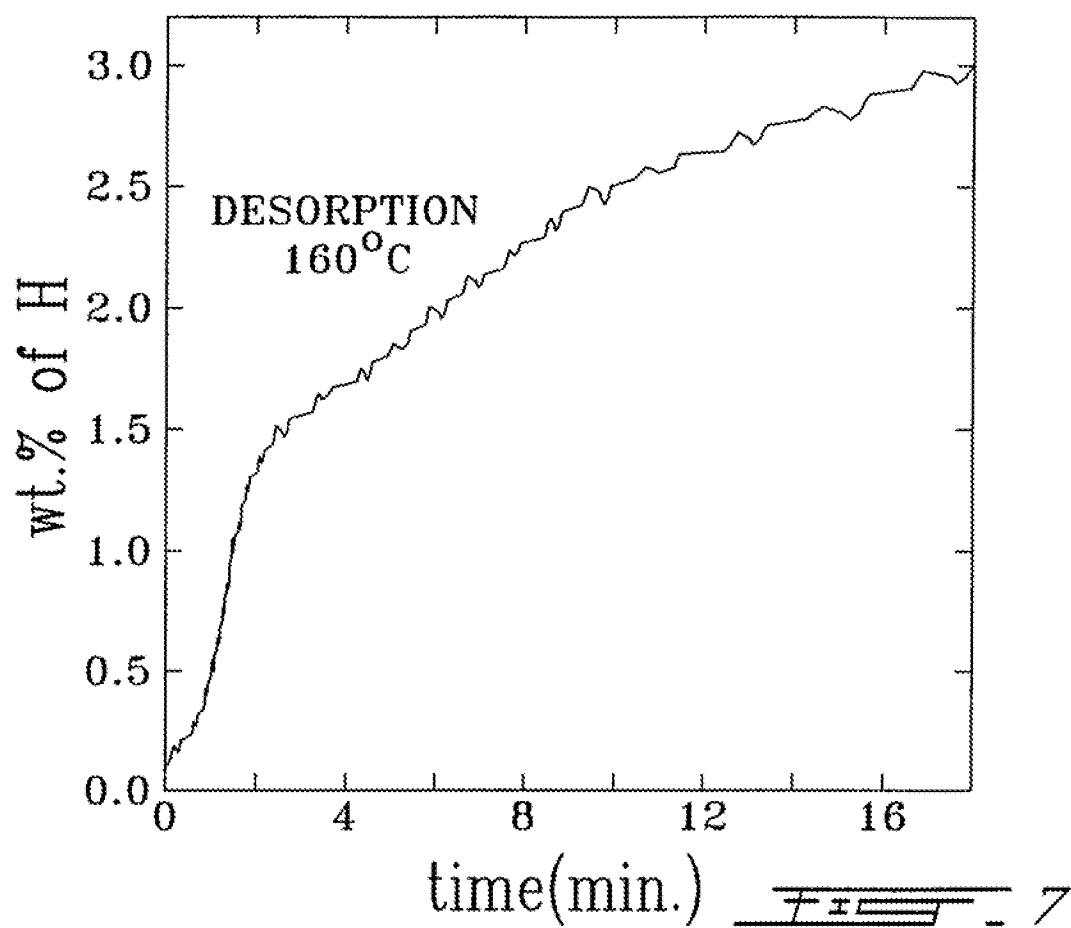


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INTERNATIONAL SEARCH REPORT

International Application No.

PCT/CA 98/00947

A. CLASSIFICATION OF SUBJECT MATTER

IPC 6 C01B3/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 C01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	BOGDANOVIC B ET AL: "Ti-doped alkali metal aluminium hydrides as potential novel reversible hydrogen storage materials" JOURNAL OF ALLOYS AND COMPOUNDS, vol. 253-254, 20 May 1997, page 1-9 XP004089146 cited in the application see the whole document	1,4,5,7, 9,14
X	DE 195 26 434 A (STUDIENGESELLSCHAFT KOHLE MBH) 23 January 1997 cited in the application see page 2, line 41 - line 59 see page 3, line 51 - page 4, line 24 see claims	1,4,5,7, 9,14

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

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INTERNATIONAL SEARCH REPORT

Internat'l Application No

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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